STATE OF ILLINOIS
ADLAI E. STEVENSON, *Governor*
DEPARTMENT OF REGISTRATION AND EDUCATION
NOBLE J. PUFFER, *Director*

DIVISION OF THE
STATE GEOLOGICAL SURVEY
M. M. LEIGHTON, *Chief*
URBANA

CIRCULAR No. 157

SHORT PAPERS ON GEOLOGIC SUBJECTS

Present State of Knowledge Regarding the Pre-Cambrian Crystallines of Illinois

By Robert M. Grogan

Factors Affecting Measurement of Permeability of Unconsolidated Glacial Material

By Robert D. Knodle

Facies Analyses of the Niagaran Rocks

By Heinz A. Lowenstam

Physical Characteristics of the Oölite Grains of the Ste. Genevieve Formation

By Raymond S. Shrode

REPRINTED FROM THE TRANSACTIONS OF THE ILLINOIS STATE ACADEMY OF SCIENCE
VOL. 42, PP. 97-119, 1949

PRINTED BY AUTHORITY OF THE STATE OF ILLINOIS

URBANA, ILLINOIS

1950

GEOLOGY

PRESENT STATE OF KNOWLEDGE REGARDING THE PRE-CAMBRIAN CRYSTALLINES OF ILLINOIS*

ROBERT M. GROGAN
State Geological Survey, Urbana

The oldest sedimentary strata of Illinois rest on a foundation of igneous and metamorphic rocks which are commonly referred to as the pre-Cambrian crystallines or basement complex. Rocks of corresponding age crop out in the nearby states of Wisconsin, Minnesota, Iowa, and Missouri, but in Illinois they are buried under a variable thickness of later sediments and can be examined only in cuttings or cores from deep wells.

Six wells in Illinois penetrate these crystalline rocks, one each in Boone and DeKalb counties, two in Lee County, and two in Pike County, figure 1. The four wells in the northern counties encountered granite, but the two southern wells encountered rhyolite porphyry and granophyre. From 3 to 639 feet of these ancient igneous rocks were cut in the various wells. All were drilled as oil tests and all but one, the Herndon Drilling Co.—Campbell well in Pike County, were drilled with cable tools.

Data regarding the names of the wells and their locations, the depth and sea-level elevation of the tops of the crystalline rocks, and their thickness and character are given in table 1. The greatest and least depths are 3845 and 2221 feet respectively. In terms of elevation, the highest occurrence is 1401 feet below sea-level and the lowest is 3046 feet below sea-level, a range of 1645 feet. As a measure of the local relief involved, the difference in elevation of the crystalline surface is 356 feet in the two Lee County wells which are five miles apart, and 1088 feet in the two Pike County wells which are 8½ miles apart.

Fig. 1.—Location of wells that penetrate pre-Cambrian crystalline rocks.

* Published with permission of the Chief, Illinois State Geological Survey.

TABLE 1.—PRE-CAMBRIAN CRYSTALLINE ROCKS IN ILLINOIS WELLS

Name of well	Location	Top of crystalline rocks		Thickness penetrated, feet	Type of rock encountered
		Depth in feet	Sea-level elevation		
1. Northern Illinois Oil and Gas Co. Taylor No. 1	28-43N-3E Boone County	2925	–2105	73	Gray granite
2. Paul Schulte, Wyman No. 1	35-41N-5E DeKalb County	3845	–2935	639	Red granite
3. H. O. Carr, Vedovell No. 1	35-20N-10E Lee County	3465	–2690	187*	Red granite and felsite
4. Amboy Oil and Gas Co., McElroy No. 1	30-20N-10E Lee County	3760	–3046	12	Red granite
5. Herndon Drilling Co., Campbell No. 1	15-4S-5W Pike County	3204	–2488	3	Red–brown rhyolite porphyry
6. Panhandle-Eastern, Mumford No. 1	21-5S-4W Pike County	2221	–1401	5	Red granophyre

* As of April 26, 1949; well reported shut down.

From the limited information provided by the six wells and the character of the topography of exposed and buried pre-Cambrian surfaces in nearby areas,[1] it is inferred that the buried pre-Cambrian terrain in Illinois probably ranges from a broadly undulatory surface studded with scattered residual hills to one featured at least in part by close-spaced hills and valleys, and that a local relief of as much as 1000 feet may be a common situation. Regional warping and local faulting and folding in post-Cambrian time have doubtless modified the original attitude of this terrain. It has been suggested that the crystalline surface becomes generally lower eastward from the Ozark dome region of Missouri and southward from Wisconsin until it reaches depths greater than 11,000 feet below sea-level in southeast Illinois.[2]

Study of cuttings shows that with the exception of altered felsite encountered in the H. O. Carr—Vedovell No. 1 well in Lee County, the crystalline rocks found in the four wells in the northern part of the State all are red or gray granites of medium to coarse-grained texture. The common essential minerals in-

[1] Buckley, E. R., Geology of the disseminated lead deposits of St. Francois and Washington Counties; Missouri Bur. Geology and Mines, Vol. 9, Part 1., pp. 17-18, 1909.
Weidman, Samuel, The geology of north central Wisconsin; Wisconsin Geol. and Nat. His. Survey, Bull. No. 16, pp. 385-395, 1907.

[2] Workman, L. E., and A. H. Bell, Deep drilling and deeper oil possibilities in Illinois; Illinois Geol. Survey Rept. Inv. 139, p. 2060 and figure 14. Reprinted from Bull. Am. Assn. Petroleum Geologists, Vol. 32, No. 11, 1948.

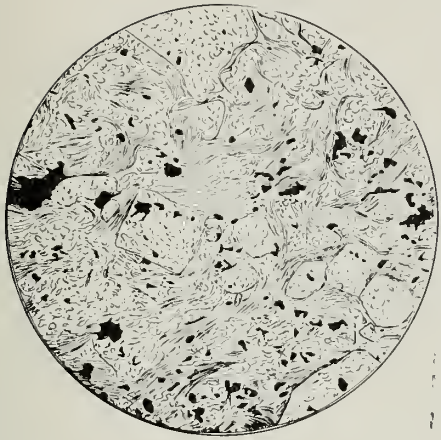

Fig. 2.—Sketch of microporphyritic felsite from dike in granite from H. O. Carr-Vedovell well, Lee County. Rectangular crystals represent altered feldspar; bundles of curving lines represent crystallites arranged in flowage pattern; black represents opaque minerals; and the rest is cryptocrystalline material. Magnification 120X.

clude quartz, orthoclase and microcline feldspar, and biotite. The common accessory minerals are apatite, zircon, rutile, magnetite, and ilmenite. Chlorite and epidote also occur in small amounts. Plagioclase feldspar is present in such small amounts as to be practically an accessory mineral; oligoclase and andesine are the varieties found. Hornblende is rare or lacking in all except the Northern Illinois Oil and Gas Co.—Taylor well in Boone County, in which it is abundant. The granite in the Taylor well also differs from the other granites in that it is grayer, contains abundant titanite, much of which is in large grains, and has andesine rather than oligoclase as its plagioclase feldspar. This difference in mineralogical character might result either from compositional variations within a single granite mass or from the presence of a separate and different body of granite at the Taylor well locality.

From a petrographer's point of view, the most interesting feature of these northern wells is the altered felsite found in the granite in the H. O. Carr—Vedovell well, which because of its much different textural character is presumed to occur as dikes intrusive into the granite. The well penetrated successively 95 feet of granite, 35 feet of altered felsite, 52 feet of granite, 7 feet of altered felsite, and finally 3 feet of granite. The least-altered particles of felsite recovered in the cuttings are reddish and purplish brown in color, and as seen in thin section, figure 2, are composed of numerous tiny square to rectangular crystals of altered feldspar in a matrix consisting of numerous crystallites and of cryptocrystalline material of indeterminate composition which may have been glass originally. The crystallites around many of the tiny feldspar crystals are arranged in a pattern suggestive of flowage while the mass was still partly fluid.

The felsite has been altered to a light green waxy clay, whose X-ray diffraction pattern is that of a mica-montmorillonite mixed layer mineral in which the proportion of mica to montmorillonite is about 5 to 1.[3] The progressive nature of this alteration, presumably by chemically active hot water which traversed fractures alongside or within the dikes, may be observed in the appearance of various fragments in the samples. It is reflected first in a change in color

[3] X-ray analysis by W. F. Bradley, Chemist and Head, X-ray Division, Illinois Geological Survey.

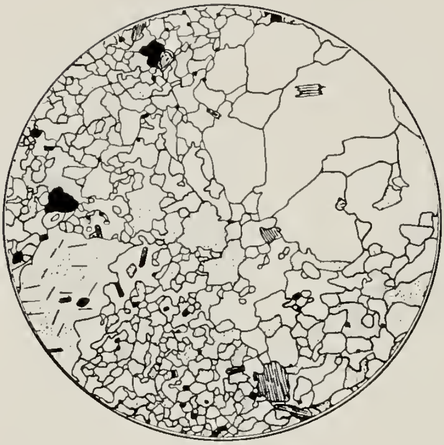

Fig. 3.—Sketch of rhyolite porphyry from Herndon Drilling Co.—Campbell well, Pike County. Clear grains are quartz, stippled are feldspar, black are mostly magnetite and pyrite, and grains with longitudinal lining are biotite and muscovite. Large areas of quartz appear as single grains in plain light. Magnification 48X.

Fig. 4.—Sketch of micropegmatitic texture in granophyre from Panhandle-Eastern-Mumford well, Pike County. Quartz (clear) is intergrown with feldspar (dashed line pattern). Black grains are magnetite. Magnification 33X.

from brownish to mottled shades of tan and greenish gray and a slight decrease in hardness, then by increasing dominance of the green color and further decrease in hardness until in the final stage the entire mass is changed to soft green clay. In thin section the original microporphyritic texture of the felsite is clearly preserved in the green clay, a further proof that the latter is an alteration product of the felsite. Additional evidence that this alteration was caused by hydrothermal solutions is afforded by the presence of small fluorite crystals in the upper part of the uppermost dike and in the 45 to 50 feet of granite overlying the dike, the somewhat altered appearance of the granite immediately above the uppermost dike, and the presence of moderately abundant pyrite in the green clay.

The crystalline rocks in the Pike County wells are distinct petrographically from the granites found in the northern wells. The rock from the Herndon Drilling Co.—Campbell well is a purplish-brown rhyolite porphyry and that from the Mumford well a granophyre. Both of these rocks are fine-grained members of the granite clan and both are types common in the pre-Cambrian exposures approximately 125 miles south in the St. Francis Mountain area of southeastern Missouri.[4]

The rhyolite porphyry in the Campbell well consists of large crystals of feldspar and quartz up to 7 millimeters long, comprising together about 20 percent of the rock, in a

[4] Erasmus Haworth, Crystalline rocks of Missouri: Missouri Geol. Survey, Bulletin 8, pp. 81-222, 1895.
Tarr, W. A., Intrusive relationship of the granite to the rhyolite (porphyry) of southeastern Missouri: Geol. Soc. America, Bull. 43, pp. 965-992, 1932.

fine-grained, equigranular, fresh-looking groundmass consisting of 60 percent quartz and 40 percent orthoclase feldspar, figure 3. Other minerals present include minor amounts of muscovite and biotite mica, chlorite, pyrite, magnetite, hematite, zircon, and garnet. The large feldspar crystals include microcline, othoclase, and microperthite, and many of them have rectangular or partly rectangular outlines. The large quartz crystals are oval to lenticular in outline, and are made up of groups of interlocking smaller crystals. The edges of many of the large quartz grains are scalloped or embayed in the fashion commonly attributed to corrosion of early-formed crystals by the still-liquid portion of magma. Many of the large crystals have been fractured, either during flowage of the mass while partially liquid or as the result of later metamorphic shearing. The cracks in some of the crystals are filled with later quartz and in others by portions of the quartz-feldspar groundmass. Further evidence of flowage or shearing is faintly apparent in traces of banding caused by parallelism of the long axes of lenticular quartz grains and a slight color banding. In general, the equigranular mosaic texture of the groundmass and the completely random orientation of the micas suggest recrystallization as a result of metamorphism. The rock has been termed a recrystallized quartzite by some, but the large amount of feldspar in the groundmass and the general non-detrital appearance of both the individual crystals and the rock as a whole make this interpretation questionable.

The original character of the crystalline rock from the Panhandle-Eastern—Mumford well, the other Pike County occurrence, is more difficult to determine as the available samples consist entirely of fragments smaller than 1/8 inch. However, it is apparent that the rock is red in color and consists largely of quartz and the feldspars microcline and orthoclase. The very minor amount of accessory minerals includes magnetite, chlorite, zircon, fluorite, and pyrite. The overall texture is an uneven medium-grained mosaic of quartz and feldspar with a few larger rectangular microcline crystals which probably are phenocrysts. Thus the rock is probably a porphyry. The most conspicuous textural feature is the abundance of an intergrowth of quartz and feldspar in micropegmatitic fashion, figure 4. Porphyries of the type described are commonly termed granophyres and this name is therefore applied to the rock from the Mumford well.

In connection with the description of the crystalline rocks of Illinois, the Insane Asylum or City Sanitarium well in the city of St. Louis is of interest as it has been reported to have reached granite.[5] This well was drilled in 1869, at which time its depth of 3843½ feet, as originally reported, made it one of the deepest wells in the world. More recently the Missouri Geological Survey gives the total depth as 3883 feet[6] from which it is inferred that the well was deepened sometime in its history.

The original published log of the well reported that the last 40 feet

---

[5] Broadhead, G. C., On the well at the Insane Asylum, St. Louis County: Trans. Acad. of Sci. of St. Louis, Vol. 3, pp. 216-223, 1878. The occurrence of granite in this well is also mentioned in an anonymous note in American Jour. Sci. 3rd Series, Vol. 9, p. 61, 1875.

[6] Communication from Edward L. Clark, State Geologist, February 25, 1949.

drilled was hard red granite because cuttings contained grains of red quartz and feldspar[7] and this interpretation has been repeated in succeeding publications that made reference to the well. Lately the Missouri Geological Survey kindly supplied cuttings from the St. Louis well from depths of 3522 to 3848 to allow comparison of the reported granite with the granites in Illinois. Study of the samples indicates, however, that no granite or other crystalline rock was encountered, but that the material penetrated was entirely sandstone, in part feldspathic and shaly. Feldspar is present in the upper samples from 3522 to 3620, absent in the middle samples from 3620 to 3817, and increasingly abundant again in the lowermost samples. Mottled shale is present in various places. No mica was observed, nor any evidence that any of the quartz or feldspar grains came from the drilling of a quartzite or granitic rock. The most reasonable interpretation appears to be that the lower part of the St. Louis well to a depth of 3848 feet penetrated a thick sandstone section containing occasional feldspathic sandstone beds and beds of mottled shale.

[7] Broadhead, G. C., op. cit.

FACTORS AFFECTING LABORATORY MEASUREMENT OF PERMEABILITY OF UNCONSOLIDATED GLACIAL MATERIAL[1]

ROBERT D. KNODLE
Illinois State Geological Survey, Urbana

Introduction

Many noteworthy contributions have been made by scientific research on the flow of fluids through porous media. The work has been mainly in two categories, consolidated material and filtration materials, with less attention to unconsolidated water-bearing materials. Many of the same problems confront the worker in all three fields, and much of the information and many concepts are interchangeable. There are, however, certain problems in the study of unconsolidated water-bearing deposits which are not encountered in the study of either filtration or consolidated material. The consolidated material tends to be more uniform in character (excluding materials with secondary porosity). Filtration material may be sorted, stratified, and of varying shape to obtain the desired results or effects. In natural unconsolidated water-bearing material, a marked heterogeneity is usually encountered; therefore a more empirical approach is necessary in their study.

Properties of Sediments

Classification.—Numerous methods have been devised to describe and classify sediments. Some are extremely useful whereas others are of limited use and little practical value. A brief review of some of the criteria is necessary to ascertain those which are pertinent to the present study. Krumbein[2] says of the mass properties of sediments, "Just as the behavior and functions of a complex organism are the sum of the behavior and functions of the component cells, so also is the character of the aggregate sediment (or any other particulate substance) a summation of the characters of the individual particles or grains of which it is made."

Packing.—An important factor which exercises control over both porosity and permeability is packing. Graton and Fraser[3] have recognized two classifications of packing, systematic and random. They have recognized six basic patterns for systematic packing, which range from loosest to closest packing. Random or disorderly packing is far more common in nature and therefore of more interest to the hydrologist and geologist.

They further state[4] that haphazard packing being of higher porosity than tighter rhombohedral packing has a larger average size of voids;

---

[1] Published with the permission of the Chief, Illinois State Geological Survey, Urbana, Illinois and based, in part, upon Master's thesis, University of Illinois.

[2] Krumbein, W. C. and Pettijohn, F. S., Manual of sedimentary petrology, p. 498, D. Appleton-Century Company, New York, 1939.

[3] Graton, L. C. and Fraser, H. J., Systematic packing of spheres with particular relation to porosity and permeability: Jour. Geol. vol. 43, pp. 485-800, 1935.

[4] Op. Cit., p. 876.

therefore it has a higher permeability. Since most haphazard packing is systemless, the voids are generally of non-uniform size, producing a higher permeability than systematic packing of the same porosity.

Porosity.—Porosity is the percentage of pore space in the total volume of the sample, i.e., the space not occupied by solid mineral matter. Fraser[5] has listed the following seven factors which control the porosity

1. Absolute size of grain.
2. Non-uniformity in size of grain.
3. Proportions of various sizes of grains.
4. Shape of grain.

Factors of more general nature include:

5. Method of deposition.
6. Compaction during and following deposition.
7. Solidification.

Size.—Slichter[6] in his theoretical work came to the conclusion that the absolute size does not affect the porosity. The factor which has been overlooked is that spherical particles were used instead of natural grains. Actually as grain size decreases, friction, adhesion, and bridging become increasingly important because of the higher ratio of surface area to volume and mass. Therefore, the smaller the grain size, the greater the porosity. Lee and Ellis[7] made determinations on 36 samples ranging from coarse sand to silt with the following results in percentage of total voids: Coarse sand, 39-41 percent; medium sand, 41-48 percent; fine sand, 44-49 percent; fine sandy loam, 50-59 percent. The average of the thirty-six samples was 45.1 percent. Smaller particles were found to give values ranging from 50 to 95 percent.

The variety in grain size in proportion of various sizes and degree of assortment must be taken into consideration in any study of porosity. A mechanical screen analysis can best express these variations.

Hazen,[8] in his experimental soil work, devised a method of gaining a simple quantitative expression of the degree of uniformity which he calls the uniformity coefficient. This is the ratio of the diameter of a grain that has 60 percent by weight of the sample finer than itself to the diameter of a grain that has 10 percent finer than itself. Results of other workers[9] have shown that the values used by Hazen are not always applicable to all types of material. However, the variation is so slight that it does not seem necessary to change the values. Hazen further noted that uniformity coefficient would range from a value of 1, if all particles were of the same size, to 20 or 30 for heterogeneous material; that is, the coefficient increases as porosity decreases. A rough estimate of the open spaces can be made from the coefficient of uniformity. Sharp-grained materials having uni-

[5] Fraser, H. J., Experimental study of the porosity and permeability of clastic sediments: Jour. Geol., vol. 43, p. 916, 1935.

of natural unconsolidated deposits.

[6] Slichter, C. S. Theoretical investigation of the motion of groundwaters: U.S.G.S., Nineteenth Annual Report, 1897-98.

[7] Lee, C. H. and Ellis, A. J., Geology and groundwaters of the western part of San Diego County, California: U.S.G.S., Water Supply Paper 446, pp. 121-23, 1919.

[8] Hazen, Allen. Some physical properties of sands and gravels with special reference to their use in filtration: Mass. State Board of Health, 24th Ann. Rept., p. 50.

[9] Terzaghi, Karl and Peck, R. B., Soil mechanics in engineering practice, pp. 21-22, John Wiley and Sons, 1948.

formity coefficients below a value of 2 have nearly 45 percent open space as ordinarily packed, and sands having coefficients below 3 as they occur in banks, or artificially settled in water, will usually have 40 percent open spaces. With more mixed materials the closeness of packing increases until, with a uniformity coefficient of 6 to 8, only 30 percent open space is obtained, and with extremely high coefficients almost no open space is left. With round-grained water-worn sands the open space has been observed to be from 2 to 5 percent less than for sharp grains of similar size.

Permeability. — Permeability as defined by Tolman[10] is the capacity of water-bearing material to transmit water, measured by the quantity of water passing through a unit cross-section in a unit time under a 100 percent hydraulic grade. Many factors influence the permeability, including size of interstitial openings, continuity of openings, surface tension, capillarity, size of grains, absolute viscosity of fluid (in centipoises), and dissolved gas. It is beyond the scope of this paper to delve into all the hydrologic aspects, but they should be recognized. Although dependent on porosity, there is no direct ratio between porosity and permeability. Terzaghi and Peck[11] have stated that "when a soil is compressed or vibrated, the volume occupied by its solid constituents remains practically unchanged, but the volume of voids decreases; as a consequence the permeability of the soil decreases."

[10] Idem, p. 114.
[11] Idem, p. 44.

With openings of capillary and sub-capillary size the molecular attraction of water molecules is sufficient to "lock" the water in the interstitial spaces.

Surface tension of fluids.—Surface tension in fine-grained sediments exercises important control. It has been estimated by King[12] that the surface area in a cubic foot of sand composed of particles 0.02 millimeter in diameter is about 50,000 square feet. It is apparent that a considerable amount of water can be contained as a thin film on the surface of the grains of such fine material, and that molecular cohesion causes any remaining interstitial space to be filled with captive water. It can be demonstrated that in a given volume of material in which all factors other than size remain equal, the total interstitial space varies inversely with the size of the interstices. A half-inch sphere has one-fourth the surface area of a one-inch sphere, but a container of one cubic inch capacity will hold eight half-inch spheres which in effect doubles the interstitial surface.

Shape.—The shape of particles is known to affect both porosity and permeability, but thorough quantitative work on this aspect has been meager.

Shape studies.—Shape studies[13] were conducted to see whether a measurable quantitative relationship exists between shape, porosity, and permeability. An arbitrary scale[14] was set up based upon three shapes,

[12] King, F. H., A text of physics of agriculture, Madison, Wis., p. 124, 1900.
[13] Wadell, H., Sphericity and roundness of rock particles: Jour. Geol., vol. 41, pp. 310-331, 1933.
[14] Rittenhouse, Gordon, Analytical methods as applied in petrographic investigation of Appalachian Basin, U.S.G.S., Circular 22, March, 1948.

Fig. 1.—Selected pebbles used as a guide in shape studies.

rounded, semi-rounded, and angular. Three specimens were picked from the samples and photographed. This photograph (fig. 1) was used as a guide in further grain counts.

A piece of metric cross-section paper placed between two pieces of lucite served to delineate a given area. Small portions of a sieved sample were placed on the ruled piece of lucite and examined under a microscope. Grains within a given area were counted and an estimate was made of the percentage of each of the three shapes. A less rapid but more accurate method would be to make counts from photomicrographs.

Methods of Analysis

It can be readily seen that to the hydrologist permeability is much more important than porosity. A sediment which possesses porosity but not permeability is useless as an aquifer.

Numerous graphical and statistical methods have been devised by various workers in an attempt to analyze sediments. A review and appraisal is desirable to ascertain which of these methods is pertinent to the present problem.

Mechanical size analysis.—Two common and widely used statistical devices are the histogram and the cumulative curve. There are certain limitations and variations attendant to these methods, some of which are discussed below. Udden[15] was among the first workers in the field of sedimentation to use histograms. He observed that histograms of sediments varied considerably according to the type of sediment involved. Beach sands have well defined modes whereas glacial till fractions are widespread and irregular and often bi-modal. One of the greatest difficulties involved in the use of the histogram is caused by the choice of class intervals used in an analysis, i.e., its shape varies according to the particular class limits which are chosen. It is therefore quite possible to construct two very unlike histograms from the same sediment merely by using different class intervals. The basic difficulty with the histogram is that it appears to illustrate continuous frequency distribution as though it were made of discrete classes. Hence the histogram may not furnish much visual information about the frequency distribution considered as a continuous variation of size.

The use of the cumulative curve was prompted by the difficulties encountered in the histogram. This curve remains fairly constant regardless of the class limits used, whereas the histogram is definitely affected by a choice of class limits. Thus the cumulative curve is a much more reliable index of the nature of continuous distribution of particles of sediment. Another advantage of

[15] Udden, J. A., The mechanical composition of wind deposits, Augustana Library Publications, No. 1, 1898.

this curve is the ease with which other statistical data may be derived from it.

Size analysis coefficients.—One of the most valuable measures is that of the median, which is the mid-point in size distribution of the sediment of which one-half by weight is composed of particles of smaller diameter than the median and one-half is composed of particles larger than the median. This is readily obtained from the cumulative curve by noting the diameter at the intersection of the 50 percent line and the curve. This value is used in the recommendations for well screens by the Illinois State Geological Survey.

Skewness, or the measure of the degree of asymmetry of the cumulative curve, has been recommended by some as a method of ascertaining the sorting; that is, a positive skewness indicates that a preponderance of the sample lies on the coarse side of the median. A negative skewness would indicate the opposite. The use of skewness currently has little practical application, mainly because relatively little is known of this character of sediments. Sampling errors, selective transportation, and other factors often manifest themselves as skewness.

Effective size was a term developed by Hazen[16] in his work on filtration sands to designate the diameter of the size particle of which they were 10 percent of the sample by weight smaller and 90 percent by weight larger. Although this measurement was derived for use on a certain sediment, it has with some modifications been quite generally accepted. The effective size is readily obtained from the cumulative frequency curve by ascertaining the point at which the 90 percent line intersects the curve. Hazen justified the choice of effective size upon his observations that the finest 10 percent of a sample has as much effect on the properties as the coarsest 90 percent.

[16] Idem, p. 432.

Trask[17] has proposed a method of expressing the measure of the average quartile spread, the coefficient of sorting. It is determined by the square root of the third quartile diameter divided by the square root of the first quartile diameter. This method eliminates the size factor, that is, differences in coarseness between samples or units of measures have no effect on the coefficient of sorting. This method gives a relative idea of the sorting in terms of well sorted (less than 2.5), medium sorted (about 3.0), and poorly sorted (4.5 or more), but fails to give an accurate quantitative measure.

Krumbein and Monk[18] conducted experiments on unconsolidated glacial sediments to determine the effect of size perameters on permeability. The results of their work are of little value in this study because their samples were artificially compounded to fit a predetermined curve, that is, the sieve separates were mixed so that the mean and standard deviations could be varied at will.

Drilling and sampling techniques. The technique in obtaining well samples varies greatly from the techniques used in other methods of sam-

[17] Trask, P. D., Origin and environments of source sediments of petroleum: Nat. Research Council, Rept. Comm. on Sed., pp. 67-76, 1932.

[18] Krumbein, W. C. and Monk, G. D., Permeability as a function of size perameters of unconsolidated sand: Amer. Inst. Min. Met. Eng. Inc., Petroleum Technology, July, 1942.

pling. It is impossible to remove the material of well samples in an undisturbed condition. Material which has slumped from higher levels in the well bore often contaminates the samples, and drilling bits often pulverize or otherwise disintegrate particles, thus distorting their true magnitude.

The type of drilling tools, the methods used, the size (diameter) of the hole, and the type of well (test hole or producing well) must be considered in the study of any given sample.

Most wells are drilled by one of three different methods—rotary, cable tool, and reverse hydraulic. Certain characteristics of each method merit discussion.

Cable tool or percussion drilling is accomplished by repeated raising and dropping of a bit and a heavy string of tools suspended on a cable or by driving casing and cleaning out the debris as the casing is forced downward, or often by a combination of the two operations.

It is difficult to obtain representative samples from cable tool bore holes. The upper portions are often drilled "dry," that is, with just enough water to facilitate drilling and bailing operations. When a water-bearing sand is encountered, the bore hole is loaded with fluid to, or in excess of, hydrostatic balance with the formation in order to prevent heaving. Heaving can cause drilling difficulties as well as contamination of samples. The constant influx of sand from a heaving formation makes it difficult or impossible to ascertain the true position and character of the water-bearing zone. Excessive disintegration of material is often caused by certain operations of the drilling procedure. Casing set with a drive shoe tends to disturb the formation, and failure of the bailer to remove cuttings exposes them to repeated blows from the drilling bit. The importance of a good and experienced driller cannot be overemphasized. It is generally the driller who collects samples, and the validity of the samples is largely dependent on his care, knowledge, and experience.

In rotary drilling, mud is of prime importance. Many holes drilled in glacial drift utilize as drilling mud the clay material found in the upper portion of the drift, adding only water. When sandy zones are encountered, additional fine-grained material, such as bentonitic clays, must be added by the driller to maintain the mud at the proper weight and viscosity and to remove the cuttings. In some cases, lime, cement, or other materials may be added to increase viscosity or weight.

Care in removing samples is necessary. A device similar to a wire box is generally used to slow up the flow of mud sufficiently to allow even the finer parts of the sample to settle before the sample is removed.

Hole size is an important consideration in the study of well samples. For example, in the large diameter wells drilled for the Illinois Water Service Company, a larger percentage of coarse particles were brought up and a larger percentage of fine particles were washed away than in the 4-inch rotary test holes drilled on the same sites.

As would be expected, information from a test hole tends to be more reliable. More care is taken in sam-

Fig. 2.—Device for measuring permeability of unconsolidated material.

pling and in other techniques. In most final wells, production is the ultimate goal. Large diameter wells produce so much material that a considerable disposal problem results, and it would be necessary to conduct a regular sample splitting procedure in order to obtain a representative sample.

Results of Studies

Permeability. — Samples used in the permeability experiments were composite samples derived from the entire water-bearing portion of University of Illinois Well No. 10. A limited number of readings were taken on 60- and 80-mesh sands and BB shot. It was of interest to note the slight variation between loosest and closest packing in the case of the 60- and 80-mesh separates. When wet samples were introduced into the permeameter containing water, they settled in a state of closest packing and any attempts to lower the permeability were fruitless.

Permeability testing.—Permeability was measured by allowing water under a 100 percent gradient to pass through a sample of known cross section and height, and measuring the amount which was passed in a given time. A permeameter was constructed of a lucite cylinder with an inside diameter of approximately 6.4 cm. and a length of 30 cm. A disc of lucite was bonded to the bottom of the tube and tapped for a 3/8 inch street *el* to which was connected a gate valve. Approximately one inch from the bottom of the tube a piece of 60-mesh wire was placed between two rings of lucite and reinforced with hardware cloth. Above this screen two openings were tapped 10 cm. apart and connected to manometer tubes which were mounted on a board with metric scales (fig. 2).

The major problem was obtaining uniform and accurate readings. To accomplish this a system of "average readings" was devised. Material was introduced into the tube in a steady stream until the top manometer opening was covered. No attempt was made to pack the material further. Water was then introduced into the tube from the top until a steady stream was obtained at the outlet, at which time a reading was taken. This first reading was taken immediately after a continuous flow was obtained through the gate valve, and recorded the permeability of the material in loosest packing.

After the permeability of the material was obtained in a condition of loosest packing a "Vibra-Tool" was used to jar the material into the closest packing possible. The flow of water was stopped during the packing process to prevent the possibility of channeling. When the closest packing possible was obtained another reading was taken. The average of the two readings was then calculated, which, in the opinion of the writer, represents most closely the original permeability of the material in place in the ground. This conclusion was reached after it was demonstrated that it was possible to produce in the laboratory both looser and closer packing than a sediment possessed in nature. By using an average of loosest and closest packing it was possible to obtain more uniform results than could be obtained by attempting to pack each sample to a uniform standard.

Several experimental readings were made in order to develop a standard procedure which would give uniform results. It was found that false results could be obtained by surging the column of sediment and allowing a relatively complete sorting to take place in the tube. Channeling was common when higher velocities were used. These channels, when developed, allowed water to flow through the column of material in a quantity far greater than in unchanneled material.

The necessity for a gate valve to control the rate of flow of water through the column of material became apparent immediately. Materials of high permeability allowed turbulent flow to develop, introducing error into the results. A high rate of flow also allowed sorting and channeling to occur, causing intolerable errors. Several readings were taken on one sample allowing different amounts of water to flow through the tube in a given time; in all cases the results were well within the limits of probable error. It was then decided to use as low a rate of flow as would register a head on the manometer gauges, thus minimizing any effects due to turbulent flow or sorting.

Hydrologic tests.—A non-equilibrium formula for determining permeability and transmissibility by well pumping tests has been developed by Theis[19] and others. This formula has been applied to a number of well tests in Illinois and apparently gives a relatively reliable indication of the permeability and transmissibility of glacial drift aquifers in place. The values so obtained are controlled by the local natural variations in porosity and permeability (and packing) plus whatever changes may have been caused by drilling and development techniques at the particular site. In one instance in the Champaign-Urbana area, the calculated transmissibility based upon the Theis formula lies about half way between the limits of permeability determined in the laboratory for maximum open packing and maximum closed packing determined with materials from the well. Other cases indicate that the aquifer transmissibility based upon such pumping tests can always be expected to be within such limits, but that the production from a well cannot be predicted from laboratory analysis.

Several factors govern the amount of water which may be derived from

[19] Idem, pp. 519-524.

a formation. Of these, proper development of the well is of great importance. In sand and gravel strata it is quite possible to over-develop a well to a point where a failure is caused in the "roof" or overlying formation. If the overlying formation is composed of clay or extremely fine sand, this material will enter the well bore, causing the material near the well to be clogged and reduced in permeability. Over-development may also cause a bridging of the fine particles between the larger ones. This condition can be generally remedied by surging, and is not considered as detrimental to the yield as roof failure.

Under-development may also cause a low yield. This occurs when insufficient pumping and surging fails to cause relatively complete sorting.

Size range of the particles and thickness of the formation have great effect on the yield of a well, as noted above. Material with great uniformity of particle size will not yield much more water after development than before.

The amount of water available and the diameter of the well are important factors in determining the yield of a well. If there is sufficient water, it is possible to utilize large diameter wells which are capable of transmitting larger quantities of water to the surface than wells of smaller diameter. A thick formation for obvious reasons is capable of containing more water than a thin one.

The factors concerning the development of wells are largely dependent on the skill and experience of the driller. In any study it is important to take cognizance of this factor.

In the shape studies conducted by the author, it was possible to determine accurately the percentage of rounded, semi-rounded, and angular grains in any given sample. However, in any consideration of porosity and permeability, the indeterminate factor of packing still remains. When dealing with uniform spherical particles Graton and Fraser[20] have shown that there are six types of systematic packing, and that porosity and permeability are definitely related to packing. Instead of dealing with six combinations as in the ideal case, it appears that in glacial drift, which is neither uniform nor spherical, an infinite number of combinations of packing can exist. Due to the extreme variability of size and shape, classification as to packing is meaningless. Therefore, any attempt to predict porosity and permeability of a finished well from laboratory samples by any mathematical or experimental process is impracticable.

Summary and Conclusions

Experimental procedure in attempting to produce uniform permeability readings illustrated very clearly that the permeability determinations in the laboratory are not indicative of the actual permeability in the formation surrounding the well bore. An experienced driller, by properly developing a well, causes its yield to differ greatly from those indicated by laboratory permeability results.

The development of a well consists of increasing the permeability of the formation in the vicinity of the well bore, which may be done by pumping and surging to remove the

[20] Idem, pp. 785-800.

fine particles from the vicinity of the well bore. The coarser sand or gravel remain behind the screen in the well bore. The entire water-bearing formation for a wide area around the well is made more uniform in grain size, affording the greatest possible voids for the water to pass through. In proper development the size of the particles gradually decreases with distance from the well bore, and the particles become firmly lodged together and stabilized so that no further change occurs. It appears impossible to predict accurately the amount of water which may be derived from a well treated in such a manner, although experienced drillers can often make remarkably accurate estimates.

After due consideration of existing studies and in the light of the present study, it becomes apparent that there is no way to evaluate quantitatively and accurately the effects of such features as roundness, size, shape, porosity, and permeability in a heterogeneous or non-uniform material with respect to its ability to produce water. In all previous works of this nature the material studied was either artificial or the original character of the natural sediments was altered to conform to desired conditions. While these studies are of academic interest they have been found to be of small value to the practicing groundwater geologist.

The use of compound samples was considered best because the production figures computed for a water well represent only the production obtained from the entire section rather than production from any single stratum.

It is concluded that the use of grain shape in predicting the yield of a formation is not practical because the effect of shape on permeability is exceeded by the effects of grain size and the manner of packing. In evaluating the factors which control porosity, permeability, and well productivity from glacial drift aquifers, it is apparent that for any given texture the effect of packing is of sufficient magnitude to minimize the effects of all other factors, so that the primary influence on an aquifer's productivity are the original conditions of deposition and its subsequent history as affecting its packing.

Acknowledgement

The author wishes to express his gratitude to Carl A. Bays, formerly Head of the Division of Groundwater and Geophysical Exploration of the State Geological Survey, for his many suggestions and the critical reading of the manuscript, to the individual members of the groundwater division staff for consultation and suggestions, and to H. E. Hudson and H. F. Smith, engineers of the State Water Survey Division, for data, suggestions, and criticism.

FACIES ANALYSES OF THE NIAGARAN ROCKS IN ILLINOIS

HEINZ A. LOWENSTAM
University of Chicago, Chicago

The Niagaran exposures in Illinois, which occur widely separated in the northeastern, northwestern, west-central, and southwestern parts of the State, contrast sharply in gross lithologic aspects as well as local facies development. The differences in gross lithology are basically expressions of broad regional facies differentiations. These regional sedimentation conditions are greatly modified in the two northern outcrop sections by a local environmental factor, the reefs, which formed local sediment sources. Complex small scale facies differentiation characterizes the reef enclosing strata here, indicating further the controlling effect that the reefs had on the sedimentation of the surrounding bottoms. These reef-bearing northern deposits stand out in sharp contrast to the reef-free southwestern Illinois deposits. The southwestern Illinois deposits consist entirely of normal shelf sediments, whereas the reef-bearing portion of the northern Illinois sections embrace reef and inter-reef deposits.

In broad environmental terms we may distinguish three major categories in the facies analyses: normal shelf deposits, reef deposits, and inter-reef deposits.

The normal shelf deposits consist principally of two recognizable source components: (1) terrigenous clastics, derived from the bordering land areas, and (2) skeletal debris, both calcareous and siliceous, supplied by the organisms that populated the shelf bottoms. The terrigenous clastics were apparently derived chiefly from the Appalachian upland or its southern extensions, and to a minor extent from the Ozark Island that existed in Niagaran time. Only in the Ozark bordering outcrop areas in southwestern Illinois do we find evidence of a major contribution of Ozark derived sediments. As to the other outcrop areas, their contributions appear to have been largely confined to the Joliet deposits of west central Illinois and the basal Joliet deposits of northeastern Illinois. There is no evidence at present to warrant the recognition of a chemical precipitate constituent in the carbonate fraction of the normal shelf deposits.

The reef facies differs radically from the shelf facies, as well as the inter-reef facies, in that it constitutes isolated bodies of essentially pure carbonate rock which is entirely organic in origin except for the secondarily introduced magnesian element. The reef frame was erected solely by reef-building organisms, principally stromatoporoids and tabulate corals, which produced rigid topographically raised structures that extended from the surrounding bottoms upward into the agitated surface waters. The interstices of the reef frame are largely filled with organic skeletal debris of reef dwelling organisms and reef detritus, which occur commonly cemented into the frame by encrusting stromatoporoids. The reef bodies are commonly found flanked by reef-derived detritus. Secondary dolomitization has greatly altered the original textures and largely obscured the organic character of the reef bodies.

The inter-reef facies, up to the present ill-defined and interchangeably referred to as normal or lagoonal facies, may be broadly defined as the deposits which accumulated within the orbit of the detritus laden waters of reef outwash. The inter-reef deposits thus embody two distinct source elements, a regional and a local reef-derived one, the latter forming the most characteristic criterion for distinguishing the inter-reef facies from the normal shelf facies.

With this as a background, the facies of the individual outcrops may be analyzed.

Beginning with the northeastern Illinois outcrops, the Niagaran deposits consist of a succession of normal shelf deposits through the Joliet formation, which gradually gave way in the Waukesha transition phase to reef and inter-reef development in the Racine-Guelph formations. The regional environmental factors which can be deduced from the gross character of the sediments as a whole are fairly muddy waters (as indicated by the average of 15-20 percent terrigenous clastics) and soft muddy to sandy bottoms, generally lying slightly below effective wave base. Reef growth started in sporadic form during Waukesha deposition, which is marked by semi-rough water conditions and the influx of coarse silt and very fine sand. Curiously enough the main phase of reef development came only after lowering of the sea bottom below wave base, implying that deeper bottoms and fairly muddy waters were not detrimental to the Niagaran reef builders. Complex facies differentiation goes hand in hand with the main reef development, the inter-reef facies shifting horizontally and vertically in correspondence to the shifting reef spread. The inter-reef deposits are characterized by sharp horizontal facies differentiations ranging from quite muddy deposits of anaerobic through aerated quiet water facies all the way to rough-water deposits which are principally composed of reef-derived detritus. The inter-reef deposits thus contrast sharply with the early Niagaran normal shelf deposits; such facies changes as were gradually attained in time but not in space in the shelf deposits can be commonly found developed over short distances in the horizontal plane among the inter-reef deposits.

In the northwestern Illinois section, the Niagaran deposits also consist of a succession of normal shelf deposits in the Waukesha formation, followed by reef and inter-reef development in the Racine-Port Byron sequence. The facies contrast between normal shelf, reef, and inter-reef deposits is here less sharply defined, the chief contrasting features being sediment structures and facies shifts. This is primarily due to the negligible content of terrigenous clastics which average here less than 5 percent. Textural and compositional criteria readily recognizable in limestones, which would aid in the analyses of a more detailed facies differentiation, have been obscured by secondary dolomitization. The broad environmental factors that characterize (and at the same time contrast) the northwestern and northeastern Illinois deposits are prevalent shallow-water bottoms, located largely above wave base, and clear water conditions. During the prevailing intervals of shallow water conditions, reef detritus was spread and redeposited entirely over the adjacent inter-reef bottoms, largely in the form of shifting sand bars rather than in detrital fans which, however, accumulated around reefs during periods of temporary subsidence below wave base.

The Niagaran deposits of west-central Illinois, as far as preserved, underlying the pre-Middle Devonian erosion surface, consist entirely of normal shelf deposits. As even the most extensively preserved sections in the Grafton area do not extend upward into the horizons of the reef-bearing strata in the northern outcrop areas, it is uncertain whether reef and inter-reef facies were originally present or not. The sections in the Hambury area consist of crinoidal limestone coquinas, of the semi rough-water type, whereas the Grafton deposits comprise dolomitized rough-water deposits at the base followed by semi rough-water deposits of the Waukesha facies type as developed in northeastern Illinois.

The southwestern Illinois deposits are represented in their entirety by normal shelf deposits in which the carbonates consist of limestone. Following an intial phase of semi rough-water conditions marked by clastic semi coquinas, the bulk of the succeeding section is composed of muddy bottom, quiet water deposits, evidently laid down at greater depth than any of those of the other outcropping areas. The prevailingly low density in burial population (consisting of small fragile forms) and lack of evidence of large scale reduction of the terra rosa muds derived from the adjacent Ozark upland point toward deposition under quiet water conditions, near or at the photosynthetic ceiling. Because of the pronounced muddiness, reflected in the terrigenous clastic content of about 40 percent, a considerably higher average than in any of the other areas, the photosynthetic ceiling was evidently above 600 feet, appreciably higher than its maximum extent under clear water conditions.

PHYSICAL CHARACTERISTICS OF THE OOLITE GRAINS OF THE STE. GENEVIEVE FORMATION*

RAYMOND S. SHRODE
Illinois State Geological Survey, Urbana

The usual hand specimens and thin sections of oolite afford randomly oriented cross-sections of the oolite grains and permit observation in one plane only. They give inadequate information therefore regarding the size, shape, or roundness of the grains. It was found that "chalky" oolite could be successfully disintegrated to yield a high percentage of discrete grains by a procedure known as the "sodium sulfate soundness test"[1] which duplicates roughly the disruptive action of freezing water but produces disintegration more rapidly. The quarry at Anna, Illinois, contains in its upper part a bed of Ste. Genevieve oolite 6½ feet thick which responded well to this procedure. This paper describes the results of a study of the oolite grains freed from six samples taken from the bed, each sample representing a vertical thickness of about 12 inches.

After disintegration each sample was screened into Wentworth size-scale fractions and weighed. The weight and number of oolite grains in a small weighed quantity of each size fraction was then determined and their particle size distribution calculated in percent by weight and percent by number.

Two matters bear critically on the confidence with which subsequent data may be regarded, namely, is the number of unbroken, discrete oolite grains proportionate to the number in the original sample, and to what extent did the disintegration process reduce the size of the freed grains by exfoliation of concentric deposits. Estimates of the abundance of oolite grains indicate that the number freed is roughly proportionate to the number in the original sample. Signs of exfoliation were generally absent in the discrete grains. This evidence and the excellent preservation of small fossils freed along with the oolite grains suggest that exfoliation was probably not an important phenomenon.

Size of Oolite Grains

The results of particle size determinations on the oolite grains in the six samples are shown in Figure 1. Most of the grains are between 0.25 and 0.83 millimeter in diameter. In terms of the Wentworth size scale for sediments, the grains are principally medium and coarse grained if considered on the basis of percent by weight. However, in terms of percent by number the dominant size is medium grained.

The particle-size histograms of the different samples show no consistent trend from the top of the bed downward. Mostly such variations as occur are between the medium- and coarse-grained grades.

The bedding and other characteristics of the stratum from which the

[1] A.S.T.M., Designation C88-46T.

* Published with the permission of the Chief, Illinois State Geological Survey.

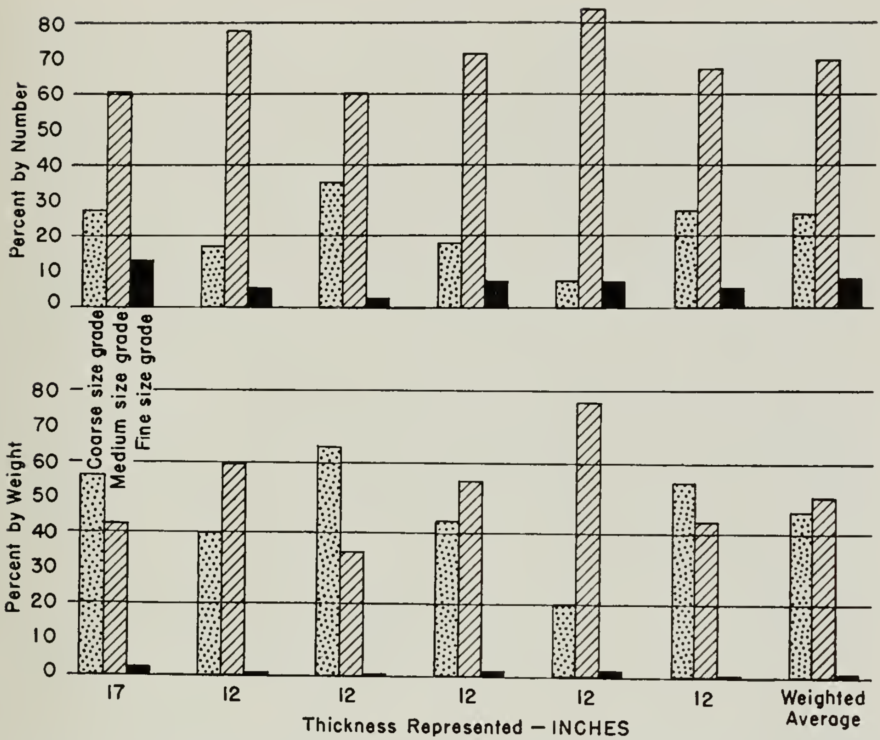

FIG. 1.—Particle-size distribution of oolite grains by weight and number. Reading from left to right the histograms progress from the top of the bed downward.

samples studied were obtained show clearly that it is a clastic rock. The particle-size data indicate conditions of sedimentation which appear to be even more selective than those under which a medium- and coarse-grained sand would be deposited. The restricted size range of the majority of the grains, about 0.6 mm., may be the result of either a high degree of sorting by the transporting medium, limiting factors controlling the maximum and minimum size of oolite grain development, or a combination of both. Erosion during transportation might also be responsible, at least in part, for the grain-size distribution. If this were true, very fine-sized oolite grains should be present. Also, some grains should show evidences of erosion, such as exposure of their internal structure. As neither of these phenomena was observed it is concluded that erosion of grains did not significantly affect particle-size distribution.

Taken together, the foregoing data suggest that the source of the oolite grains was not far from their site of deposition, that they were transported by relatively strong currents or waves, and that conditions in the area of oolite grain formation may have been such as to restrict maximum and minimum oolite size, especially the former.

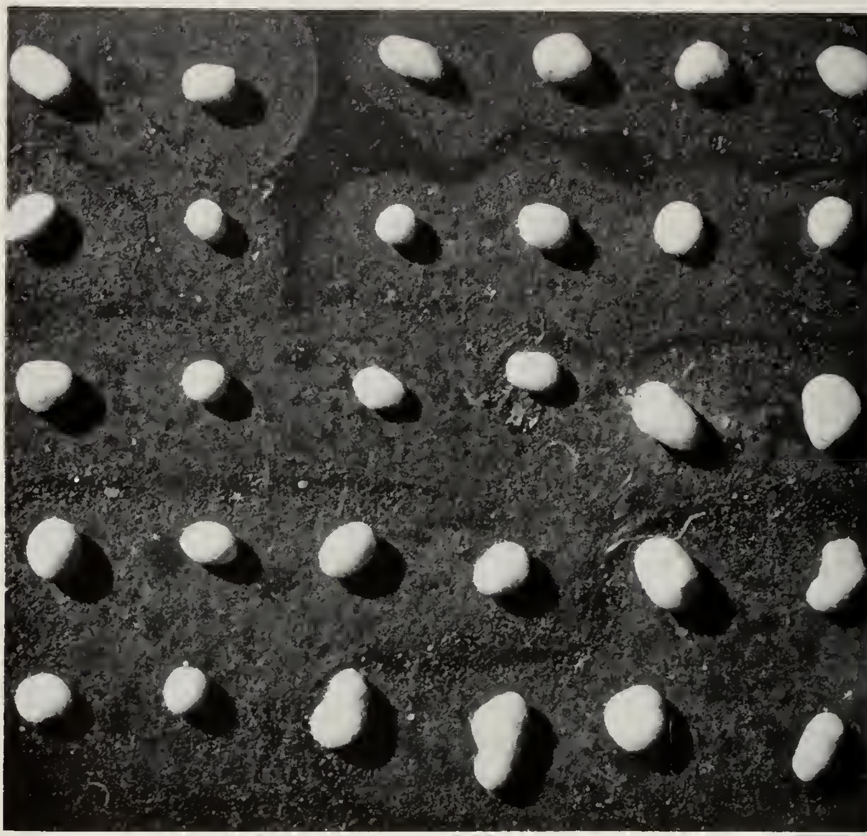

Fig. 2.—Typical oolite grains from the coarse size grade. X 10.

Shape and Roundness of Oolite Grains

Roundness determinations were made from photographs of 60 grains of each size category selected at random from the various samples. Figure 2 shows grains of the coarse sand grade. Figure 3 gives the results of classification of the grains by Krumbein's scale for roundness determination.[2] The arithmetic mean roundness values on the chart are very similar and indicate little difference in the over-all roundness of the size fractions. The coarse sand fraction, as shown by the histograms, is notably different from that of the other two size-grades. One difference is the longer 0.9 roundness bar and the shorter 0.8 and 0.7 bars. This may be interpreted as being the result of increasing roundness accompanying the growth of the oolite grains. The reason for the greater percentage of grains with 0.6 roundness in the coarse sand grade is not understood. There is some evidence, however, which suggests that the centers in these oolite grains have

[2] Krumbein, W. C., Measurement and geological significance of shape and roundness of sedimentary particles, Jour. Sed. Pet., vol. 11, pp. 64-72, 1941.

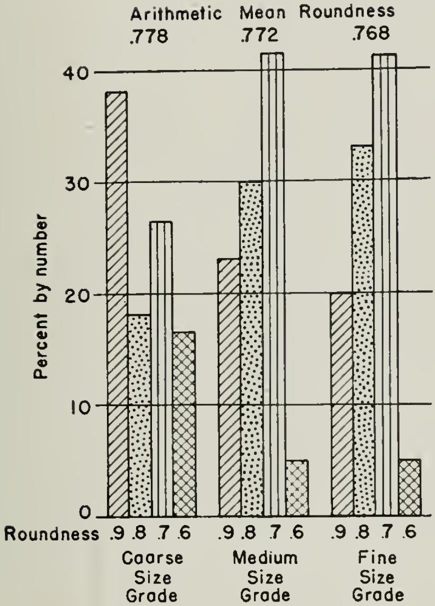

Fig. 3.—Roundness of oolite grains by size grades. Arithmetic mean roundness value is shown above each histogram.

low sphericity, are fossils or comparatively large fragments of fossils, or other types of material, and that the number of concentric deposits is small and therefore insufficient to eliminate the original angularity of the central grains.

Interesting light is shed on the reliability of roundness or shape interpretations from thin sections by a consideration of figure 2. It is evident that random sections through the oolite grains would be very misleading in many cases. A diagonal section through the elongate grains in the upper left hand corner would show an oval cross-section whereas a section at right angles to the long axis would give a circular section. Similarly erroneous results would be obtained with many of the oval or roughly triangular grains.

Summary

The oolite grains of the Ste. Genevieve limestone bed studied have the size characteristics of a well sorted medium- and coarse-grained sand and do not appear to have been transported far. Their roundness values are all higher than 0.5. There is suggestive evidence that the growth of oolite grains is accompanied by an increase in roundness. The three dimensional shape character of the oolite grains suggests that detailed shape interpretations from thin sections may be misleading.